Natural Materials as a Pathway to Affordable and Scalable Membrane Separation Technologies

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Focal area

Critical mineral (CM) extraction from geothermal brines aligns with geothermal power plant operations, enabling simultaneous energy production and resource recovery with minimal environmental impact and water loss. Conventional CM extraction processes are typically energy- and water-intensive; in contrast, this approach leverages geothermal energy to significantly reduce both energy demand and water use.

Existing challenge

Geothermal power plants can play a vital role in meeting America's growing energy demand. The hot geothermal brines often contain minerals or elements of interest such as Li, and other critical minerals (CMs) such as manganese (Mn) and barium (Ba).[1] These species exist in very low concentrations within these geothermal brines.[2] However, these species are often comparatively abundant in quantity. For example, the geothermal brines located in the Salton Sea, CA, is estimated to have enough Li to replace all of the cars in the United States with electric vehicles (EVs).[3] Therefore, finding a way to tap into these valuable resources with minimal water usage has the potential to secure the CM domestic supply chains, as well as provide opportunities for robust energy technologies, such as enhanced grid storage. Both of these strategies serve to maintain the United States' energy sovereignty and decrease reliance on foreign imports of valuable resources.

Traditional Li extraction methods often involve evaporation, a method that can take years to produce useable Li compounds, making it nonviable for processes that require further use of the Li depleted water.[4] Extraction of these geothermal mineral resources shows promise, as a direct lithium extraction (DLE) module can easily be placed in line with the geothermal energy generation process. After the heat is extracted from the geothermal water, the cooled water can be run through a module that strips the valuable species, and then the depleted water will be returned to the reservoir. However, the technology is not mature and there is significant need for further development.[5] Likewise, CM species such as Ba and Mn are often mined from solid sources.[6,7] These mining techniques can be intensive processes, utilizing large volumes of water and energy which can also present significant hazards to both people and the environment. By extracting these species from geothermal brines, a new supply stream with lowered environmental impact is accessible. This approach would ensure that the water levels within the reservoirs are not depleted and remain viable for geothermal energy applications. Unlike other extraction processes this approach does not require extra water resources, and can utilize energy from geothermal wells directly.

The difficulty of extracting high value products (e.g., Li, ~200 mg L^{-1}, Ba ~200 mg L^{-1}, Mn ~1000 mg L^{-1} in the Salton Sea) from low concentration aqueous sources is further complicated by high concentrations of undesirable species (Ca >50,000 mg L^{-1}, Na >20,000 mg L^{-1}, etc.).[2] An extraction technology therefore needs to be highly selective towards CMs and capable of handling large volumes of brine without prohibitive material cost, while minimizing energy and water consumption. Since no commercial DLE technology has been fully demonstrated, there is significant opportunity to expand this field and meet a growing supply chain need.[5]

Near term opportunity

The near-term opportunity lies in developing technologies capable of processing large volumes of brine with high selectivity and efficiency, minimizing energy and water use. Membrane separation technology is a particularly promising candidate with growing emphasis on ion-selective separations.[8–11] Although some commercial membranes have been tested for such applications[9], many suffer from degradation caused by fouling and mineral scaling- issues that are particularly severe in geothermal brines due to high concentrations of Ca^{2+}, Mg^{2+}, and other organic compounds. To address these challenges, we aim at developing membranes made from in-expensive, environmentally friendly, and naturally abundant materials that can be economically disposed of once they reach the end of their service life. Direct disposal of such membrane can reduce costs associated with membrane regeneration, fouling and scaling treatment, helping to over-come long-standing challenges on membrane technology. If successful, this approach could enable rapid deployment in geothermal systems.

However, because we select natural materials as the fundamental building blocks for the membrane, further research is needed to understand how such membranes can overcome the chemical similarities among CMs to achieve effective separation. For instance, Li^+, Na^+, and K^+ ions are notoriously difficult to separate due to their similar ionic radii and hydration energies. Addressing this challenge will require fundamental scientific studies to guide the low-cost design and fabrication of tailored membranes—offering an opportunity to achieve breakthroughs in long-standing membrane separation limitations.

This approach differs significantly from current membrane technologies that rely on advanced materials such as metal–organic frameworks (MOFs), hydrogen-bonded organic–inorganic frameworks, and carbon nanotubes, which face major challenges in scalability and affordability. In contrast, our strategy emphasizes accessible, natural materials—critical for delivering a fast, practical solution to meet national urgent needs.

Given the potential to customize membrane properties for specific compositions and target minerals, the applications of such membranes extend far beyond geothermal brines to include oil and gas produced water and other industrial waste streams. In the near term, there is strong potential to design membranes with the selectivity needed to extract CMs from geothermal brines and integrate them directly into existing geothermal energy plants. Depending on brine composition, multiple selective membrane units may be deployed sequentially to achieve targeted extraction of specific elements.

In addition, high-temperature heat pumps (HTHPs) can complement these systems by upgrading low-grade geothermal heat to higher, usable temperatures for industrial or district heating applications. Integrating HTHPs not only enhances overall energy efficiency but also increases the usability and economic value of geothermal resources.

Success Measures

- Successful lab-scale demonstration of membrane technology for geothermal brine, increasing the technical readiness level (TRL) level from 1 to 5. The technology should recover more than 70% of lithium from low-concentration geothermal brine with over 70% purity, suitable for subsequent ultra-refining to battery-grade lithium.
- Fundamental understanding of the impacts of membrane design and chemistry on separation performance.
- Successful tailoring of membrane designs for different compositions, target minerals, and waste streams.
- Understanding (or developing a technology that reduces the amount of water used) the reduction in water usage compared to traditional Li extraction methods.

Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. SAND2025-136630

U.S. DEPARTMENT of ENERGY NNSA National Nuclear Security Administration

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